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# Comparative Analysis of Photovoltaic Power Storage Systems by Means of Batteries and Hydrogen in Remote Areas of the Amazon Region in Brazil

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**Abstract**
This study analyzes the photovoltaic power storage comparing the traditional lead-acid batteries with electrolytic hydrogen where the gas is reconverted to power in a fuel cell. In order to design the two systems a load profile of the Brazilian Amazon communities was used as well as some practical operational data of equipment tested in the laboratory. A mathematical model was developed, implemented in a spreadsheet that considers the several devices and their efficiencies in order to specify and match the systems components. The results were employed to evaluate the economic viability of the two systems in remote communities. Considering the present conditions, it was verified that the battery system is slightly cheaper. However, it was also observed that a minor cost reduction in the electrolyser, as well as in the buffer and fuel cell would make the hydrogen system very competitive, becoming the best option for photovoltaic power storage with important benefits to the environment.

***Keywords:*** Photovoltaic Power, Battery, Hydrogen and Fuel Cell.

## 1 Introduction

Brazil, a developing country, presents high levels of energy consumption, comparable to that of rich countries. But the access to that energy is not privilege of all. It is estimated that there are about 12 million people without electricity, most of them living in rural communities and small villages in isolated areas [1].

The main characteristic of those communities is that they are disconnected from the existing Interconnected Electrical Systems in Brazil. The generation of electricity in places like that is generally made by diesel generators, whose diesel fuel is subsidized [2].

Traditionally systems based on photovoltaic panels used to attend isolated communities require a battery bank to store electricity during daylight and to supply electricity either at night or during low incidence of sunlight. However, the operational conditions of the panels and the battery bank are not always optimal, and even in the best cases the use of a large number of batteries is mandatory.

Other ways of storing energy generated by photovoltaic panels can be more interesting from the viewpoint of system optimization. In this study, a system composed of photovoltaic panels connected to a water electrolyser to produce hydrogen is considered. The gas is stored in a reservoir to be used in a standard PEM fuel cell whenever necessary.

## 2 The Mathematical Model to Assess the Energy Systems

To dimension the systems based on photovoltaic panels, it is initially necessary to know the solar radiation of the site and the characteristics of energy consumption to be met. The optimal design is the balance between the available energy and the consumption, taking into account the efficiency of the different equipment involved in the transformation [4].

As the study takes into account the profile of demand load over 24 h, it was considered the average hourly incident solar radiation during the day (4,75 kWh/$m^2$) [5]. The characteristic energy demand used belongs to the rural community of Vila Campinas/AM. Based on a study involving the community [3], a single system is proposed to attend a school, a community center, a health center and three houses totaling an electric power consumption of 10.4 kWh/day.

The mathematical model was developed using a Microsoft Excel spreadsheet where the main characteristics associated with solar radiation, equipment operation and electricity consumption profile were introduced. Some of the most important input parameters are: i) average solar radiation per hour; ii) electricity consumption of each appliance; iii) equipment efficiency; and iv) equipment minimum and maximum operational limits (voltage, pressure, etc.). The spread sheet can provide as output data the amounts of used, stored, and wasted energy over 24 hours per day, by each piece of equipment as well as the whole system. Figures 1 and 2 show the arrangement of the complete systems to be analyzed.

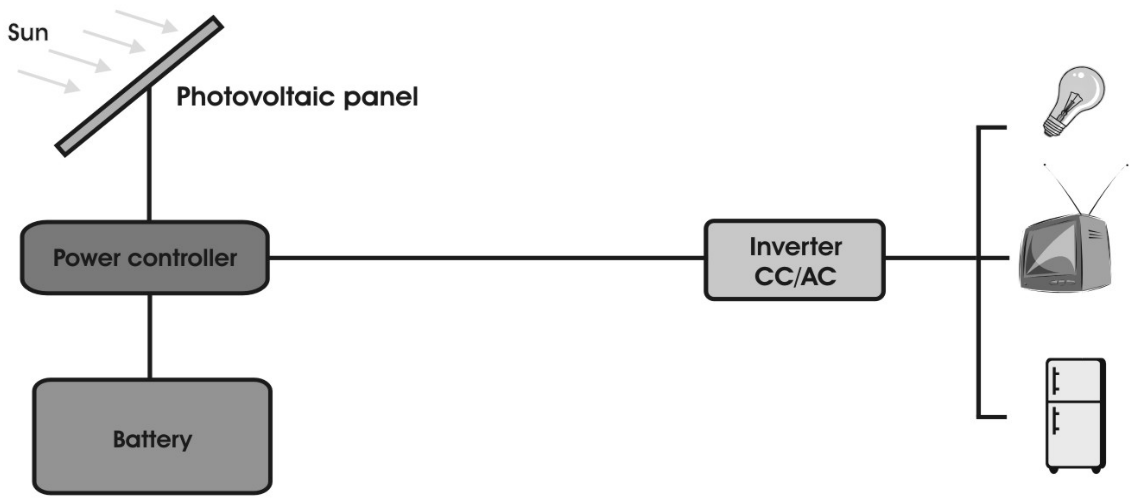


**Figure 1: Array of photovoltaic system with energy storage in batteries.**

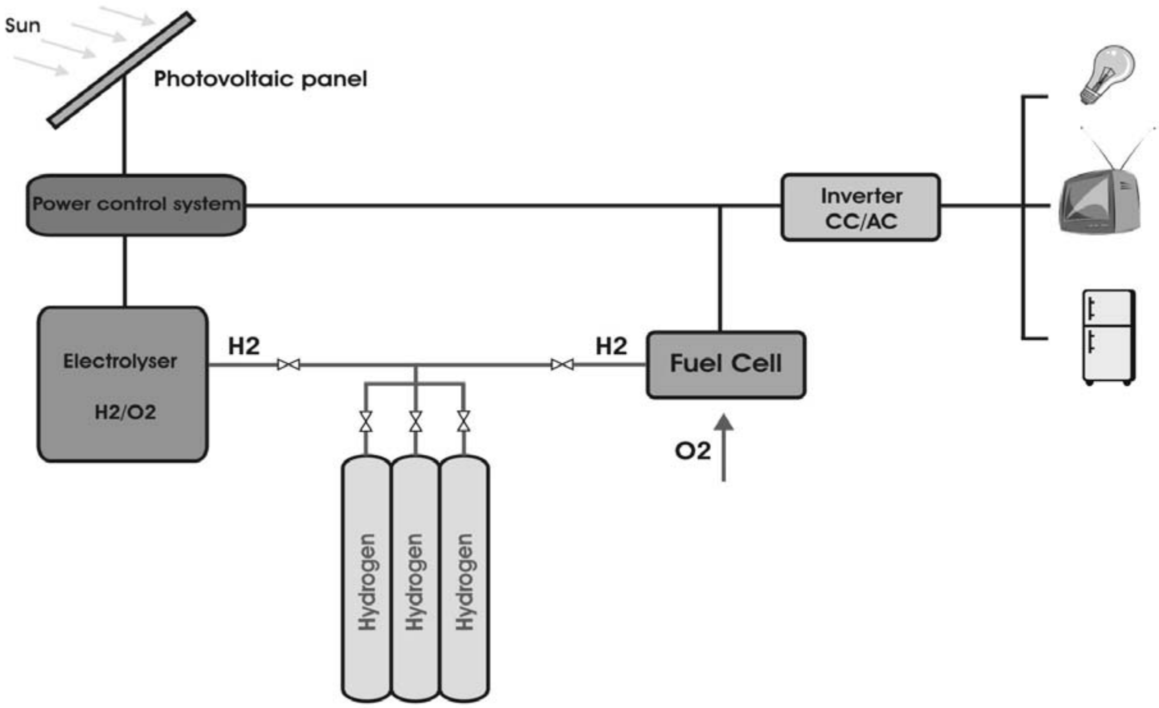


**Figure 2:** **Array of photovoltaic system with storage of energy as hydrogen.**

## 3 Results and Discussion

### 3.1 Photovoltaic panels

According to calculations, the photovoltaic system with hydrogen storage requires a larger amount of photovoltaic panels than the system using batteries, 58 and 24 respectively. This difference is related to the minimum energy required for the operation of the electrolyser (1 kWh), below which the electrolyser does not operate. On the other hand, the batteries do not require a minimum amount of energy to start the storage process, when its state of charge is below its full capacity.

### 3.2 Production, storage and conversion of hydrogen

Unlike a photovoltaic system that uses batteries as electrical energy storage, the system that uses hydrogen needs more devices to perform the functions fulfilled by batteries. Therefore, the batteries should be replaced by a device capable of: i) converting the electrical energy from the photovoltaic panels into hydrogen, i.e. an electrolyser; ii) a reservoir to store the hydrogen; iii) a device to convert hydrogen into power, i.e. a fuel cell.

An immediate comparison between the two systems includes:

**Lifetime:** The lifetimes of the devices replacing the batteries (electrolyser, hydrogen storage vessel, fuel cell) are respectively 20, 20 and 6 years, while the batteries lifetime, considering daily loading/unloading, do not exceed 4 years. So, the conventional system would require 66 batteries and 4 replacements, totalizing 330 batteries along its lifetime.

**Efficiency:** The overall efficiency of the hydrogen system, considering an efficiency of 80% for the electrolyser [7] and 50% for the fuel cell [6], is 40%, while the battery reaches 80% [8]. The lower efficiency of the photovoltaic-hydrogen system is due to the combined efficiency of the various devices required to substitute the battery pack.

**Environmental:** Lead-acid batteries contain lead and sulfuric acid, and consequently need special care to be disposed of, as they may cause environmental damages. This aspect is quite important in isolated communities where logistics for batteries' replacement and disposal is difficult. In the hydrogen system, the useful life of its main components is longer and the rate of replacement is much lower. Therefore, the equipment has reduced chances of causing environmental damages.

### 3.3 Energy produced, surplus and autonomous systems

An important feature to be considered in these systems is the amount of energy produced and stored. Figure 3 shows the typical production profile of an electric power system with photovoltaic panels and batteries, and the consumption of electricity by an isolated community in a typical day. If the batteries bank reaches its maximum state of charge and the photovoltaic panel exceeds demand, the surplus energy will not be used. This is shown at the 14 and 15 hours in the figure. In this system the energy surplus was 0.378 kWh/day.

Figure 4 presents the amount of energy stored in the form of hydrogen over the period of 24 hours, which considered the high heating value (HHV) of hydrogen to transform the quantity of gas into energy. The same approach can be made for the surplus energy, which in this case is around 0.993 kWh/day.

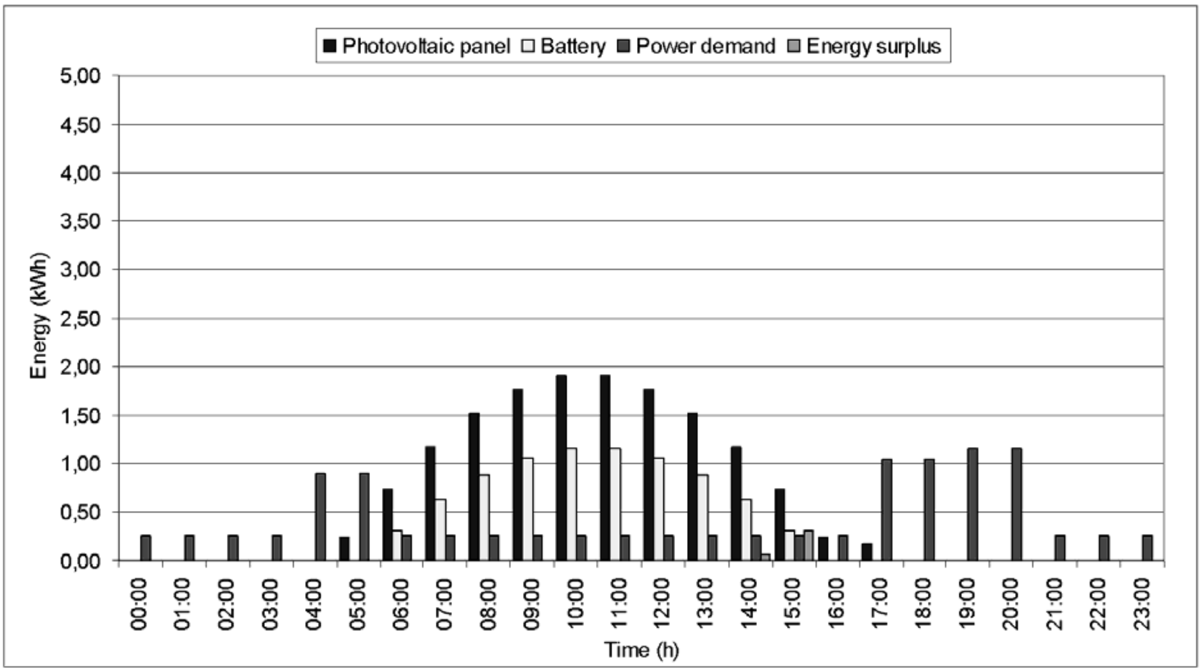


**Figure 3: Typical profile of photovoltaic system with energy storage in batteries.**

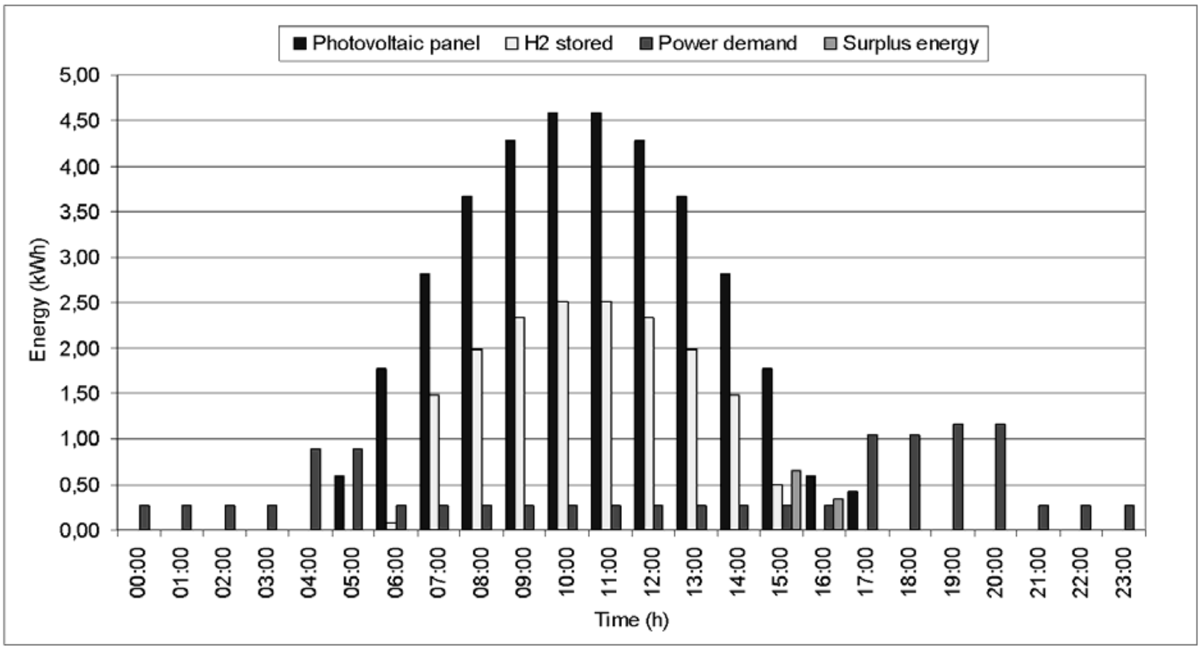


**Figure 4: Typical profile of photovoltaic system with storage energy in hydrogen.**

## 4 Conclusions

In both systems, the photovoltaic panel is the equipment that most contributed to the initial investment. Thus the total cost of the photovoltaic system with the battery was US$ 139,560.00 and with hydrogen storage US$ 168,056.00, or 20% higher. A reduction of approximately 35% in the costs of the electrolyser/hydrogen storage vessel/fuel cell makes this system economically comparable to the battery pack system. The capital cost of photovoltaic power system with batteries seems more competitive in relation to the photovoltaic system for hydrogen storage, but when a thorough consideration is done concerning environmental aspects, it can be said that the hydrogen storage system is potentially much less aggressive to the local environment than the battery system.

Therefore, using as a criterion the comparative cost of electricity produced by each system, it is possible to conclude that the photovoltaic system with battery pack still seems to be the most economically competitive than the hydrogen storage system. The expectation, however, is that with the increase in scale of production of fuel cells and electrolysers, there will be a drop in their market prices to the point of making such system viable. To support this expectation it is interesting to remember that although the PEM fuel cells have only recently reached the stage of commercialization, they are successfully replacing batteries in applications such as back-up power in telecommunication antennas, and forklifts.


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